

Time-dependent measurements of the CKM angle γ at LHCb

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The startup of the LHC opens many new frontiers in precision flavour physics, in particular expanding the field of precision time-dependent CP violation measurements to the B_s^0 system. This contribution reviews the status of time-dependent measurements of the CKM angle γ at the LHC's dedicated flavour physics experiment, LHCb. Particular attention is given to the measurement of γ from the decay mode $B_s^0 \rightarrow D_s^\pm K^\mp$, a theoretically clean and precise method which is unique to LHCb. The performance of the LHCb detector for this and related modes is reviewed in light of early data taking and found to be close to the nominal simulation performance, and the outlook for these measurements in 2011 is briefly touched on.

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1 Introduction

At the dawn of the LHC era, the CKM angle γ remains the least well measured component of the Unitarity Triangle which describes CP violation in the Standard Model. The current status of γ measurements and the motivation for measuring γ precisely are both discussed elsewhere in these proceedings [1, 2]. This document will outline the current status of time-dependent γ measurements at the LHCb experiment. One of the unique things about LHCb is its simultaneous access to large quantities of B_s^0 decays and ability to resolve B_s^0 oscillations. In particular, LHCb can measure γ from the interference in mixing and decay of the mode $B_s^0 \rightarrow D_s^\pm K^\mp$. This is a theoretically pristine [3, 4] measurement of γ , but has hitherto been experimentally inaccessible. Due to the limited space, the focus here will be on this measurement, but other time-dependent measurements are also being pursued at LHCb [5].

2 Measuring γ from $B_s^0 \rightarrow D_s^\pm K^\mp$

Before discussing the current experimental prospects, it is worth reminding ourselves of the phenomenology of this decay. The treatment here (and the LHCb measurement strategy) follows the notation and method introduced in [4].

The time-dependent CP asymmetry in the decay $B_q^0 \rightarrow D_q \bar{u}_q$ is given by

$$A(t) = \frac{\frac{1-|\xi_q|^2}{1+|\xi_q|^2} \cos(\Delta M_q t) + \frac{2\text{Im}(\xi_q)}{1+|\xi_q|^2} \sin(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2) - \frac{2\text{Re}(\xi_q)}{1+|\xi_q|^2} \sinh(\Delta\Gamma_q t/2)}, \quad (1)$$

where q stands for the d or s quark, and u_q is a pion or kaon. ΔM_q is the mass difference between the B_L and B_H eigenstates in the B_q system, and $\Delta\Gamma_q$ the decay width difference between the “heavy” and “light” B_q mass eigenstates. The sensitivity to γ comes through

$$\xi_q = -(-1)^L e^{-i(\phi_q + \gamma)} \left[\frac{1}{x_q e^{i\delta_q}} \right], \quad (2)$$

where ϕ_q is the mixing phase between B_q^0 and \bar{B}_q^0 , δ_q is a strong phase difference between the decay channels $\bar{B}_q^0 \rightarrow D_q \bar{u}_q$ and $B_q^0 \rightarrow D_q \bar{u}_q$, which is not CP-violating, and x_q represents the level of interference between the B_q^0 and \bar{B}_q^0 decaying into the same final state.

Current time-dependent measurements [6, 7] of γ from B_d^0 decays suffer from the small values of $\Delta\Gamma_d \approx 0$ and $x_d \approx 0.04$, which mean that the bottom and top left terms in Equation 1 approximate to 1, leaving only the “sinusoidal” observables in the top right term to constrain γ . It can be shown that this results in an eightfold ambiguity, and as well means that the value of x_d , computed from SU(3) arguments, must be an

external input to the fit. On the other hand $\Delta\Gamma_s$ could be sizeable, while $x_s \approx 0.4$, so that in the B_s^0 system there are three extra observables. This both reduces the ambiguity to a twofold one, because of the “hyperbolic” observables in the bottom term, and allows x_s to be fitted for directly, eliminating any SU(3) uncertainties in the measured value of γ . The measurement of γ from $B_s^0 \rightarrow D_s^\pm K^\mp$ benefits from a simultaneous fit with $B_s^0 \rightarrow D_s^- \pi^+$, which allows both Δm_s and the flavour tagging power to be fitted for directly. Taken together these facts make the extraction of γ from $B_s^0 \rightarrow D_s^\pm K^\mp$ competitive with time-integrated methods [8]; previous simulation studies [5] have indicated a precision of 10° with 2 fb^{-1} of integrated luminosity.

3 Prospects for γ from $B_s^0 \rightarrow D_s^\pm K^\mp$ at LHCb

During 2010 LHCb has collected $\approx 37 \text{ pb}^{-1}$ of data, sufficient for a first comparison with the expected [5] Monte Carlo simulation (MC) performance in these decay modes. At the time of the CKM conference only $\approx 3 \text{ pb}^{-1}$ had been collected; the results shown here therefore supersede the related conference talk.

3.1 Selection performance

The offline selection performance in this family of modes is illustrated in Figure 1 for $B_s^0 \rightarrow D_s^- \pi^+$. The offline purity and reconstruction efficiency are broadly in line with MC expectations, however the overall yield per pb^{-1} is approximately a factor two lower than expected. This is because of the running conditions encountered in October of 2010: a high number of pp interactions in each bunch crossing and a low number of filled bunches. LHCb was designed for precisely the opposite running conditions and as a result strong event multiplicity cuts had to be applied at the trigger level, leading to a decrease in efficiency.

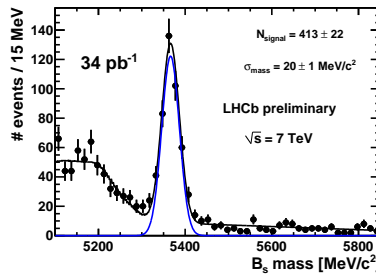


Figure 1: Selected $B_s^0 \rightarrow D_s^- \pi^+$ events, in which the D_s decays to $\phi\pi$. The total yield including other resonant and non-resonant D_s decay modes is ≈ 2 times larger.

3.2 Proptime resolution and flavour tagging

The LHCb proptime resolution is currently around 50 fs, close to the MC expectation of 40 fs. Flavour tagging at LHCb includes opposite side tagging, which infers the production flavour of the $B_{d,s}^0$ meson by tagging the “other” B decay in the event, and same side tagging, which primarily tags the production flavour of a B_s^0 meson by searching for the associated charged kaon produced in the fragmentation. The opposite side flavour tagging performance is around 60% of the nominal MC expectation, while the same side tagging performance is still under evaluation. These issues are discussed in more detail elsewhere in these proceedings [9]. A degradation in tagging power or proptime resolution results in reduced sensitivity to γ per pb^{-1} of data, but both are well within the limits required to make time-dependent CP measurements at LHCb intrinsically viable. Indeed LHCb has already observed B_d^0 oscillations, as seen in Figure 2.

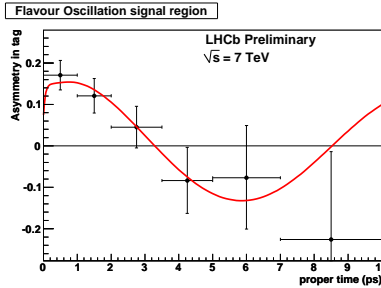


Figure 2: Oscillations in $B_d^0 \rightarrow D^* \mu \nu$ with $\approx 2 \text{ pb}^{-1}$ of data. The value of Δm_d from an unconstrained maximum likelihood fit is $(0.53 \pm 0.08) \times 10^{12} \text{ } \hbar s^{-1}$.

4 $B_s^0 \rightarrow D_s^\pm K^\mp$ and ambiguities: a closer look

As was already remarked, the measurement of γ from $B_s^0 \rightarrow D_s^\pm K^\mp$ suffers from only a twofold ambiguity in the case that $\frac{\Delta \Gamma_s}{\Gamma_s}$ is sizeable (say around 10%), but this only holds in the limit of sufficient statistics. Figures 3 and 4 illustrate this point. Note that, unlike in the B_d^0 system where the sensitivity to γ shows a significant dependence on the size of the strong phase δ_d , this result is independent of the size of the strong phase δ_s . The figures illustrate how the extra hyperbolic observables present in the B_s^0 system remove ambiguities: their likelihood in the $\delta_s - \gamma$ plane is staggered compared to the sinusoidal observables. It also shows that the $B_s^0 \rightarrow D_s^\pm K^\mp$ measurement requires a certain “critical mass” of signal events below which there is a significant bias in the measured value of γ . In this case a combined fit with the decay modes $B_d^0 \rightarrow D^{\pm(*)} \pi^\mp$ under the assumption of U-spin symmetry [4, 10] might allow for the ambiguous solutions to be partially resolved.

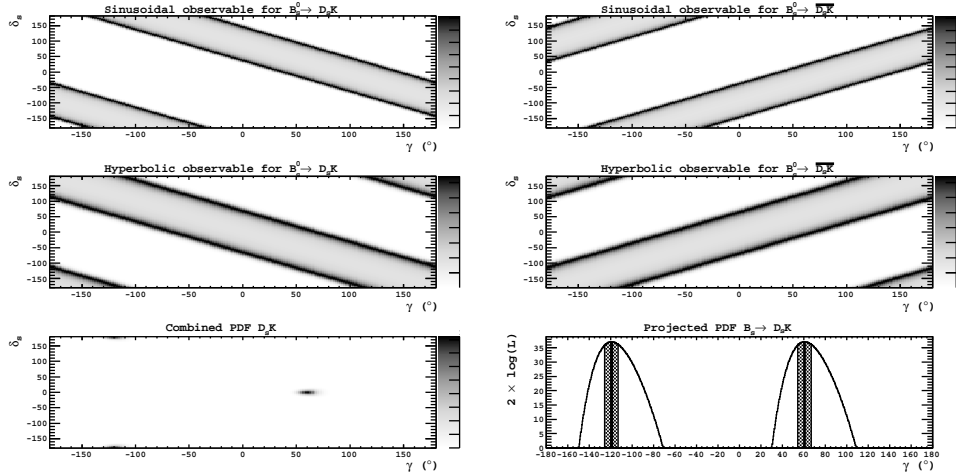


Figure 3: The top four plots show the likelihoods of the $B_s^0 \rightarrow D_s^\pm K^\mp$ CP observables with 31k signal events and LHCb MC performance [5]. The input values of γ , δ_s , and $\frac{\Delta\Gamma_s}{\Gamma_s}$ are 60° , 10° , and 10%. The bottom left plot shows the combined likelihood in the $\gamma - \delta_s$ plane and the bottom right the projection onto γ , where the thatched area is the 1σ region and the dark vertical line the central value. All but two of the ambiguities are excluded and the central value of γ is unbiased.

5 Conclusions and outlook

The long term outlook for time-dependent γ measurements at LHCb is excellent: LHCb has already very nearly achieved its nominal MC selection efficiency and proper-time resolution, and B_d^0 oscillations have been observed. The ultimate systematic limitations will not be clear until the measurement of γ from $B_s^0 \rightarrow D_s^\pm K^\mp$ has been performed, but there is no reason to suspect that any crippling problems lurk around the corner. On the other hand, the short term outlook is more uncertain. The LHC plans a long shutdown in 2012 in order to increase the beam energy from the present 3.5 TeV to the nominal 7 TeV, and it is natural to ask what precision LHCb can achieve on γ with the 2011 dataset, expected to be around 1 fb^{-1} . Extrapolating from the current yield of approximately $25 B_s^0 \rightarrow D_s^- \pi^+$ events per pb^{-1} , and adjusting for the relative yields of these modes as measured in MC studies, LHCb could expect around 2100 $B_s^0 \rightarrow D_s^\pm K^\mp$ decays in 2011. This will be enough to measure the CP observables, but not enough for an unambiguous measurement of γ . Of course, improvements are being worked on: higher trigger efficiencies, the inclusion of suppressed D_s decays, or the inclusion of related decay modes such as $B_s^0 \rightarrow D_s^\pm K_1^\mp$ in the fit. Much also depends on the poorly known branching ratio of $B_s^0 \rightarrow D_s^\pm K^\mp$, but around 4k events will be needed to have a precise measurement in 2011.

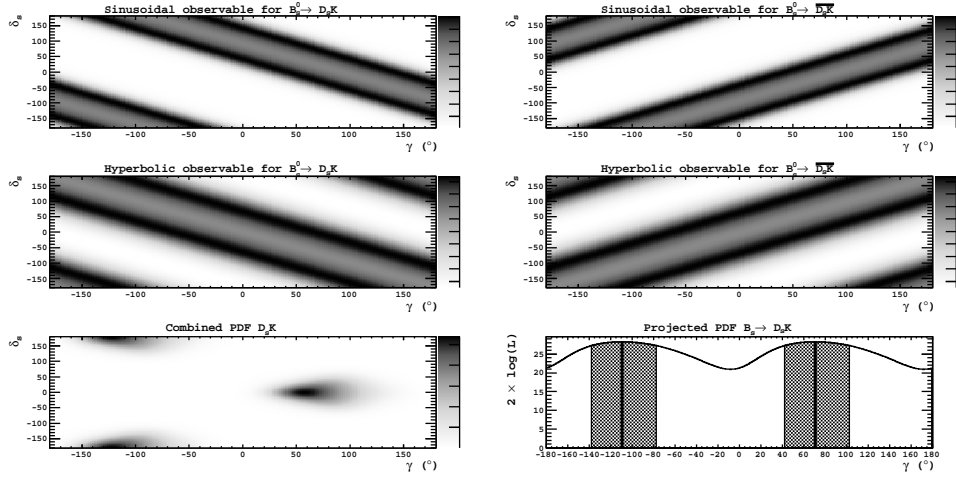


Figure 4: As Figure 3 but for 1.55k signal events. The ambiguities blend into two blocks of four degenerate solutions each, and the central value of γ is biased.

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